PHYSICAL REVIEW C **73**, 044321 (2006)

Structure of ^{26}Na from the ^{14}C(^{14}C, d) reaction

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(Received 13 March 2006; published 21 April 2006)

The ^{14}C(^{14}C, d) reaction at 22 MeV was used to study $T_z = 2$ ^{26}Na. Charged particles were detected with a Si detector telescope at 0°, and γ transitions in coincidence were detected with an array of three Compton-suppressed "clover" detectors and seven Compton-suppressed single Ge crystals. The Deuteron-γ and d-γ-γ coincidence data were analyzed to study the structure of ^{26}Na. New levels were found, and precise energies and γ-decay patterns were determined for many states previously observed in charge-exchange reactions. Candidates were observed for the 1^+ state missing in β decay. Mixing ratios were determined for some γ transitions from angular distribution information. There is reasonable agreement with the model based on the universal s-d shell (USD) interaction.

DOI: 10.1103/PhysRevC.73.044321 PACS number(s): 21.10.−k, 25.60.Je, 27.30.+t

I. INTRODUCTION

Recent research on the structure of nuclei far from stability has provided new insights into the mutability of nuclear shells and their effects on astrophysical processes. However, only very limited information can be obtained about nuclei with the most extreme neutron to proton ratios or isospin because they can only be studied with short-lived radioactive beams of limited intensity and purity. The value of this knowledge can be greatly increased by comparison with nearby nuclei of intermediate isospin which can often be studied more thoroughly using long-lived radioactive beams which provide more favorable experimental conditions.

The $Z = 11$ Na isotopes provide a relatively well explored sequence in which to study the effects of increasing neutron-to-proton ratio. Information exists from proton-unbound ^{19}Na [1,2] through stable ^{23}Na to ^{37}Na [3,4]. ^{35}Na and ^{37}Na are neutron bound [3–5], but ^{36}Na is not, and it is likely that no heavier isotopes are bound. Interestingly, the half-life of ^{35}Na of 1.5(5) ms is the shortest β-decay lifetime known [5]. Of course, the amount of information decreases rapidly away from stability.

A recent study of ^{28,29}Na from the β decay of ^{28,29}Ne showed that the "island of inversion" starts at $N = 18$ ^{29}Na in the $Z = 11$ chain of Na isotopes [6]. That is, the low-lying structure of ^{28}Na is in reasonable agreement with shell model calculations restricted to the s-d shell using the universal s-d shell (USD) interaction [7], in contrast to ^{29}Na. Instead, the low-lying structure of ^{29}Na agrees reasonably well with Monte Carlo shell model (MCSM) calculations which include the f-p shell [8]. The MCSM calculations predict a 50% admixture of f-p configurations in the ground state (g.s.) of ^{29}Na, but they predict significant f-p contributions only for increasingly higher energy states with decreasing neutron number. ^{27}Na is better known because it has been studied not only by means of β decay [9], but also through in-beam particle transfer and particle-γ measurements [10,11]. However, much less was known about its lighter neighbor ^{26}Na before the present work.

Another open question in the even mass Na isotopes is the issue of the missing 1^+ states. In ^{26,28}Na, the USD calculations predict four 1^+ states below 3 MeV with roughly comparable β-decay log(ft) values from ^{26,28}Ne, but only three have been observed in each case [6,12].

The spin and parity of the ground state of ^{26}Na were assigned 3^+ on the basis of allowed β-decay branches to 2^+ and 4^+ states in ^{26}Mg [13,14]. Many excited states were located in ^{26}Na by a pioneering ^{26}Mg(t, ^{3}He) investigation [15]. However, no spins or decay schemes were determined in this work. A subsequent ^{26}Mg(t, ^{3}He) experiment confirmed those levels, added a few more, and provided some spin assignments through analysis of the ^{3}He angular distributions with a one- and two-step charge-exchange reaction analysis [16,17]. A recent study of the β decay of ^{26}Ne showed allowed branches to three 1^+ states in ^{26}Na [12].

II. EXPERIMENTAL TECHNIQUE

The ^{14}C(^{14}C, d) reaction at $E_{\text{lab}} = 22$ MeV was used to populate neutron-rich ^{26}Na. Beam intensities from the Florida State University Superconducting Accelerator Laboratory were about 15 nA on target. A self-supporting 600 μg/cm^2 thick ^{14}C foil was used as the target, followed by a 27 mg/cm^2 Au foil to stop the beam. This allowed placement of the charged-particle telescope at 0° relative to the beam. The telescope consisted of a 5 mm thick Si E detector and a 150 μm ΔE detector placed close enough to the target to subtend 0.82 sr of solid angle. This arrangement maximized counting rate at the expense of somewhat reduced energy resolution due to straggling in the Au foil and kinematic broadening over the range of angles subtended. Particle identification was not compromised. High resolution was provided by the γ detection in coincidence. Three four-crystal clover detectors and one single-crystal detector were placed at 90° relative to the beam. Two single-crystal detectors were placed at 35°, and four more at 145°. Deuteron-γ and d-γ-γ coincidences were recorded. Two-point angular distributions were extracted from the d-γ coincidences for the stronger lines by comparing the intensities at 90° to those at 35° and 145°.

III. RESULTS

Because ^{26}Na was produced weakly with less than 1% of the total cross section, its lines could only be seen in concidence with deuterons. Relevant portions of the γ spectrum in coincidence with deuterons are shown in Fig. 1. The ^{24}Na lines in the spectrum come from a ^{12}C contamination on the ^{14}C target. The overwhelming reaction channel was ^{14}C(^{14}C,2n)^{26}Mg, which led to a few of the strongest ^{26}Mg lines appearing in the spectrum from random coincidences. Since the level schemes of the contaminants are all well known, their lines were removed from consideration as candidates for transitions in ^{26}Na early in the analysis.

New transitions were placed in the ^{26}Na level scheme based on the energies of the deuterons in coincidence with them. Examples of the deuteron spectra in coincidence with γ transitions are shown in Fig. 2. The peaks are rather broad because the experiment was designed to improve deuteron detection efficiency at the expense of resolution. Since the gating transition may also appear at the bottom of cascades, only the highest deuteron energy gives information on the placement on the decay line. As a result, the high-energy

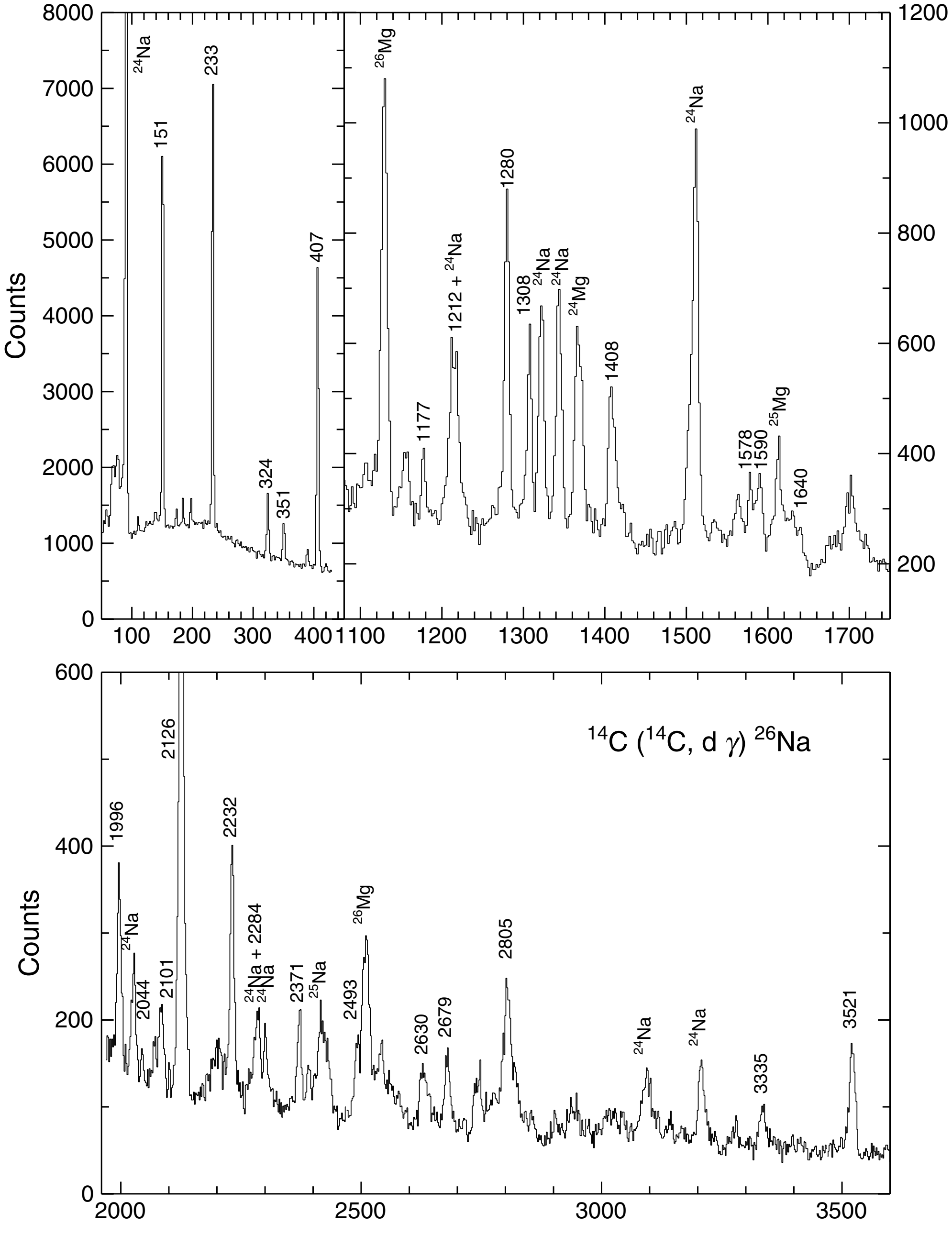

FIG. 1. Portions of the γ spectrum in coincidence with deuterons from the ^{14}C + ^{14}C reaction. Peaks assigned to ^{26}Na are labeled with their energies in keV. Peaks labeled with an isotope arise from contaminants or random coincidences.

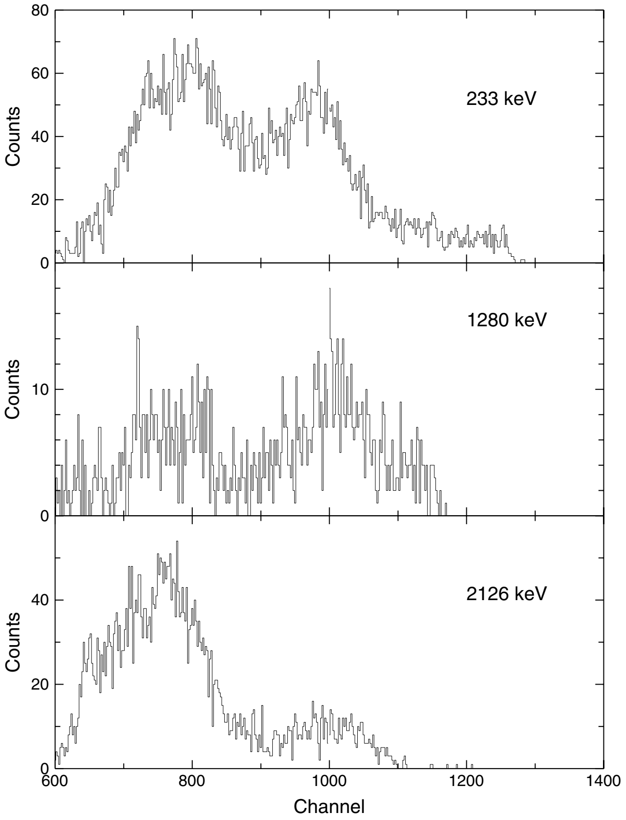

FIG. 2. Deuteron spectra in coincidence with the 233, 1280, and 2126 keV transitions in ^{26}Na.

cutoff of the deuteron spectrum was used as an indicator of the placement of the transition. The decreasing energy of the high-energy cutoff can be seen in the spectra in Fig. 2, which are gated on decays from the 233, 1513, and 2126 keV levels. Uncertainties in the deduced excitation energies are on the order of a few hundred keV, depending on the intensity of the γ line. Of course, γ-γ coincidences would provide better evidence for placement in the level scheme. However, the γ spectrum was so overwhelmed by ^{26}Mg lines that ^{26}Na lines were not clean enough in the γ-γ coincidences to be useful. The deuteron-gated γ-γ coincidences are quite clean, but have very limited statistics. Some examples are shown in Fig. 3. The long lifetime of the 82.5 keV level (9 μs) precludes d-γ-γ coincidences with its decay line.

A. Level scheme

The level and decay scheme of ^{26}Na based on the present, as well as past, work is shown in Fig. 4. For comparison, states observed in the charge-exchange reaction are shown to the left. The results of USD shell model calculations shown on the right will be discussed later. Electromagnetic decay information is also presented in Table I.

TABLE I. States and electromagnetic decays observed in ^{26}Na.

E_x (keV)	J_i^π	E_γ (keV)	Intensity (relative)	Branching ratio (%)	δ
0	3^+				
82.5	1^+				
233.3	2^+	150.9	82	45	0.16(7)
		233.3	100	55	−0.32(14)
406.5	2^+	324.1	16	16	0.14(9)
		406.5	87	84	−0.25(12)
1408		1408	33		
1513	1^+	1280	45	88	
					0.07(10)
		1107	6.5	12	
1661		1578	15		
1997		1590	17	22	
		1764	31	39	
		1996[a]	31	39	
2046		1639	7.2	50	
		2044[a]	7.2	50	
2126		2126	147		
2182		2101	2.6	15	
		1775	14	85	
2232		1996[a]	31	41	
		2232	44	59	
2284	5^+	2284	14		
2454		2044[a]	7.2	28	
		2371	19	72	
2712		2630	19		
2725	1^+	1212	25	52	
		2493	23	48	
2805		350	13	20	
		2805	54	80	
2938		2855	9.9	44	
		2938	13	56	
3223	(2^+)	1041	19	70	
		1177	8.1	30	
3305		1308	3.2		
3418		3335	20		
3603		3521	41		
4192		2679	24		

[a] There are two possible placements for this line. Intensity and branching ratio represent 100% of its strength in this decay.

The level scheme below 500 keV was well established before the present work. The levels reported in the (t,^{3}He) reaction [15] differ by 5.5, 7.7, and 13.5 keV from the more accurate determination using γ energies, that is, they lie within the stated uncertainty of ±15 keV. The present excitation energies are close to those reported in the β-decay study [12]. The 82.5 keV transition was not observed in the present work because of its long lifetime, but the difference in energy between the 233.3 and 150.9 keV lines is within 0.1 keV of the value reported in Ref. [12] for the energy of the first excited state.

No states were reported between 420 and 1996 keV in the first (t,^{3}He) work [15] because that region was obscured by peaks from contaminants. The later (t,^{3}He) experiment [16] also suffered from contaminant problems in that region, but reported an unresolved group of levels between 1.45 and 1.65 MeV and a tentative level at 1.86 ± 0.06 MeV. One state was observed in the β decay at 1511 keV in this region [12]. That state is clearly observed in the present work at 1513 keV. In addition to its dominant decay to the 233.3 keV level

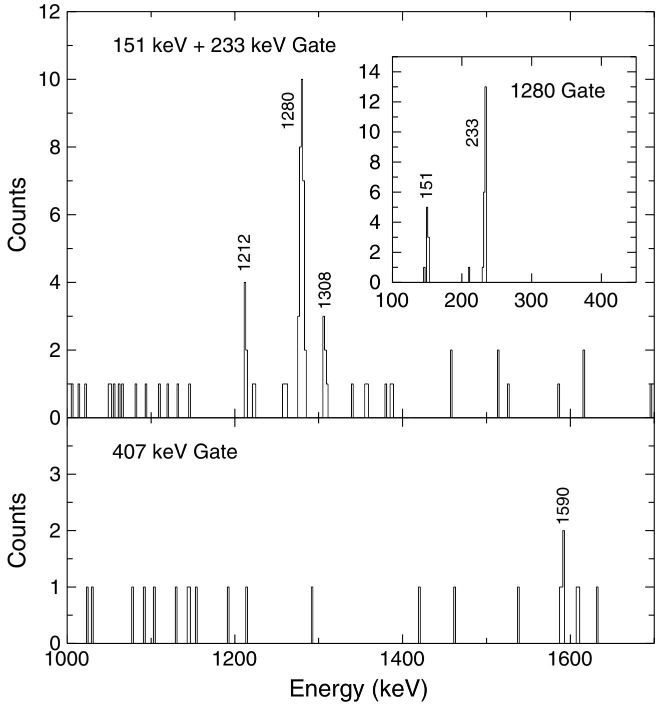

FIG. 3. γ spectra in coincidence with deuterons and the indicated γ lines.

reported in Ref. [12], we also see a decay branch to the 406.5 keV state. Coincidences between the strong 1280 keV decay line to the 233.3 keV state and the 150.9 and 233.3 keV decay lines from the 233.3 keV state are clearly visible in Fig. 3. Coincidences were also observed between the 1764, 150.9, and 233.3 keV lines.

The exact placement of the new levels shown at 1408 and 1661 keV is not as certain as that of the 1513 keV state. Both of the former are based on a single decay line and the coincident deuteron energy, since the only $(t,{}^3\mathrm{He})$ information is the existence of an unresolved group of states between 1450 and 1650 keV. The current placement agrees well with this energy range, but we cannot rule out placement of the decay lines to other low-lying states, especially the 82.5 keV level. No coincidences were observed betweeen the 1408 or 1578 keV lines and the decay lines from the 233.3 or 406.5 keV states. This is consistent with the placement shown in Fig. 4 or to the 82.5 keV state, although decay to the 233.3 or 406.5 keV states cannot be completely ruled out. Finally, there is no evidence in the present spectrum for decays from the tentative 1.86 ± 0.06 MeV level [16].

Five of the levels observed in the present work between 1900 and 2500 keV appear to correspond to states observed in the $(t,{}^3\mathrm{He})$ experiment [15] with energy differences ranging between 1 and 6 keV. The placement of all but one of these corresponding states is further confirmed by multiple decay branches and coincidences between the 1590 and 406.5 keV lines. It should be noted that there are two possible placements for the 1996 and 2044 keV transitions. Two proposed new levels at 2126 and 2232 keV do not correspond to peaks in the $(t,{}^3\mathrm{He})$ spectrum. The 2126 keV state is based on one strong decay line whose deuteron cutoff energy agrees well with its placement as a ground-state decay. Some caution should be attached to this state because the efficiency-corrected intensity of the 2126 keV line is larger than that of any of the low-lying transitions, an unusual situation, but not necessarily wrong if it is a ground-state transition. We have not located any contaminant which could produce such a line. The 2232 keV state is supported by two decay paths, but one of these is the possible dual placement of the 1996 keV transition.

Four more states have been identified up to 3 MeV. Three of these probably correspond to $(t,{}^3\mathrm{He})$ peaks with energy differences of 5 to 15 keV. The remaining state at 2725 keV is well established with two decay paths, coincidence relations for the stronger 1212 keV decay, and a clear correspondence with the 2723 keV state observed in the β decay of ${}^{26}\mathrm{Ne}$ [12].

Above 3 MeV, no candidate could be found in the present data for the 3123 keV level reported in Ref. [15]. There are candidates in the $(t,{}^3\mathrm{He})$ spectrum for all the states observed in the present work, with energy differences ranging from 2 to 18 keV. The placement of the 3223 keV state is further supported by two decay branches, and that of the 1308 keV line is supported by coincidences with the 150.9, 233.3, and 1996 keV lines.

B. Spin assignments

The ground-state spin-parity was assigned 3^+ from a study of the β decay of ${}^{26}\mathrm{Na}$ to 2^+ and 4^+ states in ${}^{26}\mathrm{Mg}$ [13,14]. This differs from the shell model prediction as discussed in the next section. The observation of allowed β decay from the 0^+ ground state of ${}^{26}\mathrm{Ne}$ to the 82.5, 1513, and 2725 keV states in ${}^{26}\mathrm{Na}$ provides a firm assignment of 1^+ to these three states [12]. The angular distribution information on the 1280 keV decay branch of the 1513 keV state is consistent with the 1^+ assignment, as can be seen in Fig. 5.

A spin-parity hypothesis of 2^+ provides the best fit to the $(t,{}^3\mathrm{He})$ angular distributions for the 233.3 and 406.5 keV states [16]. The angular distributions measured in the present work provide a confirmation of the 2^+ assignments to these two states. This can be seen in Fig. 5 for the decays of the 233.3 keV state to the 3^+ ground state (151 keV line) and 1^+ first excited state (233 keV line). Spin hypotheses of $2\hbar$ provide excellent fits with reasonable $E2/M1$ mixing ratios δ, whereas hypotheses of 1 or $3\hbar$ do not provide acceptable fits for one or the other decay branch, keeping in mind that the only physically reasonable $M3/E2$ mixing ratio is zero. The angular distributions for the two decay branches of the 406.5 keV state are quite similar to those of the 233.3 keV level and lead to very similar χ^2 graphs (one of which is shown in Fig. 5) and identical conclusions about spins.

The $E2/M1$ mixing ratios δ determined in the present work are listed in Table I.

IV. DISCUSSION

A. USD shell model

Shell model calculations allowing all particles outside the ${}^{16}\mathrm{O}$ core to occupy the full s-d shell and using an effective

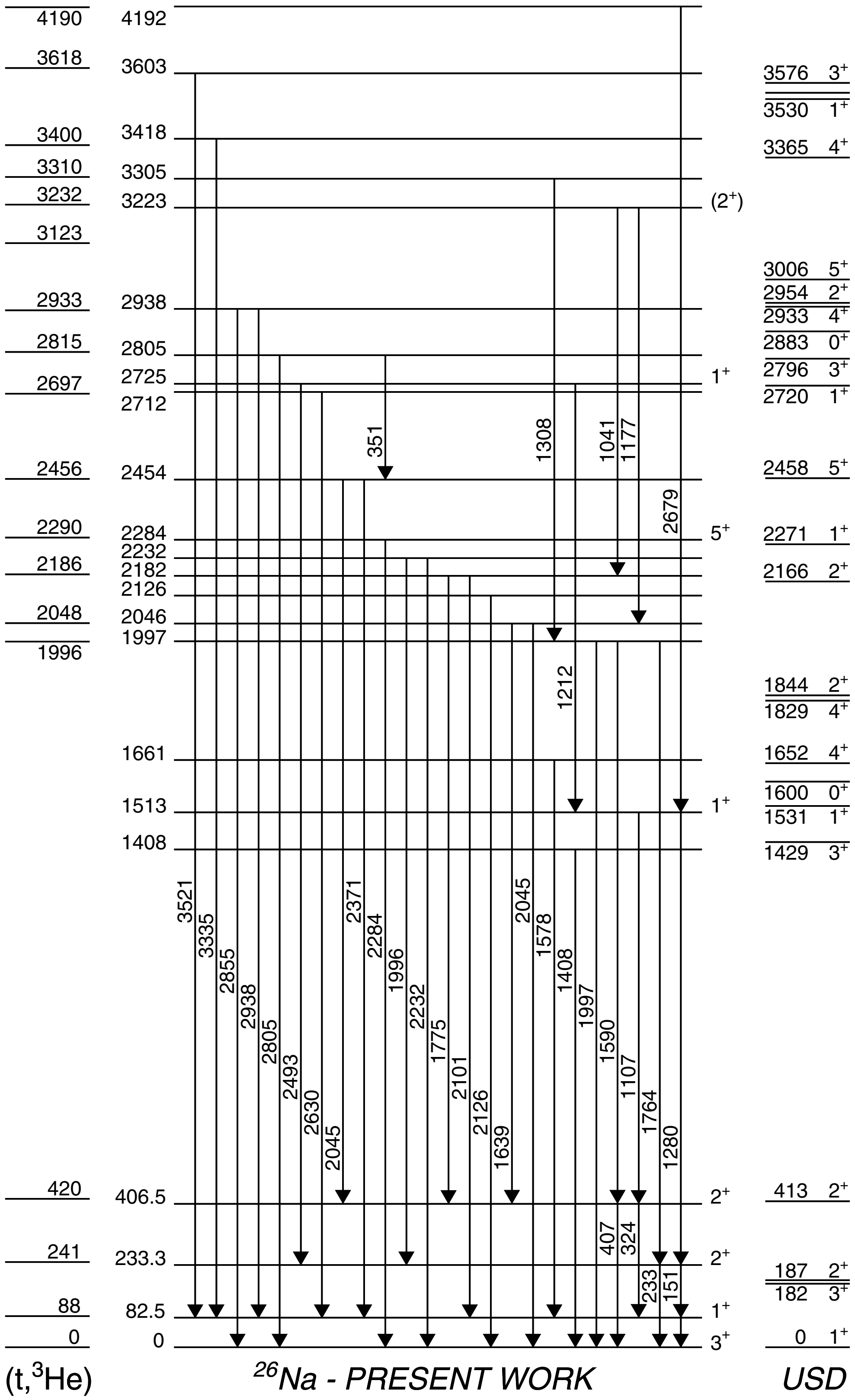

FIG. 4. Level and decay scheme of ^{26}Na in the central portion of figure is based on present and previous work, as discussed in the text. The vertical scale changes above 3700 keV. For comparison, levels deduced from the ^{26}Mg(t,^{3}He) reaction [15] are shown on the left, and levels predicted by the shell model using the USD interaction are on the right. Not all levels above 3700 keV are shown in the left or right columns.

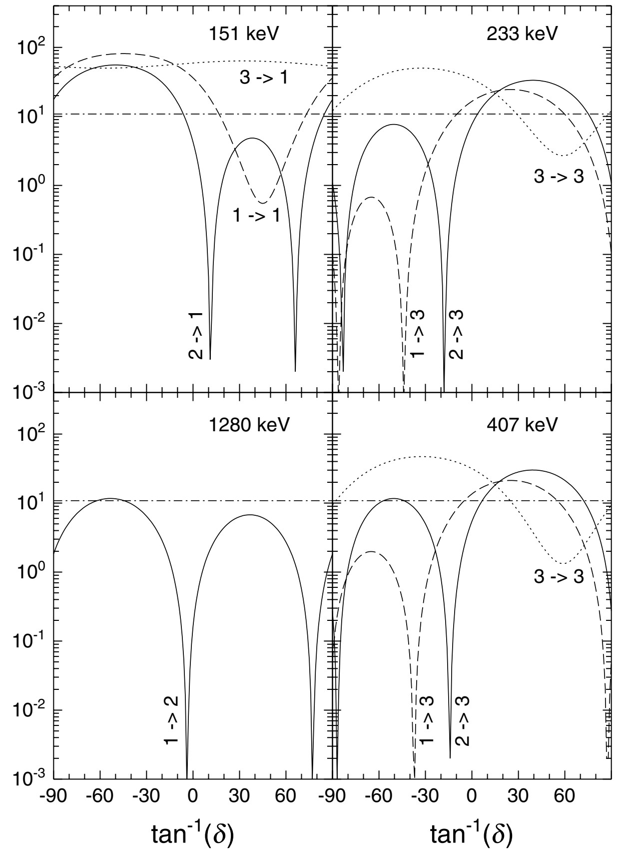

FIG. 5. Goodness of fit χ^2 as a function of the mixing ratio δ for γ transitions of 151, 233, 407, and 1280 keV. Spin hypotheses label each curve. Horizontal dashed lines indicate the 0.1% confidence limits.

interaction fitted to the structure of many *s-d* shell nuclei (USD) were performed for ^{26}Na [7]. Only the ground and first excited state were included in this fit. All the other states on the right side of Fig. 4 are true predictions.

The shell model predicts four states below 1400 keV clustered below 500 keV, in good agreement with experiment. The spin assignments are also consistent, except that the ordering of the first two states is opposite to experiment. In spite of this inversion, the r.m.s deviation between predicted and measured energies of the first four states is 103 keV, which lies at the low end of typical deviations in the *s-d* shell.

The picture is not as clear above 1400 keV. The shell model predicts six states between 1400 and 1900 keV, but only three have been observed. Since there is a larger cluster of experimental states above 1900 keV than predicted, it is likely that some of the predicted states lie a few hundred keV higher. The other possibility, which certainly cannot be ruled out, is that some states have not been observed experimentally. The 1513 keV 1^+ state agrees well in energy with the predicted 1^+ state at 1531 keV. If placed correctly, the g.s. decay of the 1408 keV state would be consistent with its identification with the 1429 keV 3^+ shell model level, but not the 1600 keV 0^+ level. The correspondence of the 1661 keV state with predicted shell model states depends sensitively on its decay mode. If it decays to the 1^+ level, as shown in Fig. 4, it probably corresponds to the 0^+ state at 1600 keV. If instead it decays directly to the 3^+ g.s., the best correspondence would be with the 1652 keV 4^+ state, but then the experimental state would have an excitation energy of 1578 keV. Both possible identifications lead to energy differences below 100 keV.

On a wider view, nine states are predicted by the shell model between 1400 and 2500 keV, and ten are shown in Fig. 4. This makes it more likely that the "missing" states below 1900 keV simply lie higher, rather than having been missed experimentally. The "extra" state in the wider energy range may result from a misplaced level, a shell model state overpredicted by 200 keV or more, or a negative-parity intruder state not in the *s-d* shell model. The somewhat isolated 2454 keV state lies very close in energy to the 5^+ shell model state at 2458 keV. However, it is not likely to correspond because its decay branch to a 2^+ state limits its possible spin to a maximum of 4^+, and 5^+ has been assigned to the 2290 keV state in the $(t,{}^3\mathrm{He})$ experiment [16]. The g.s. decay of the 2284 keV state is compatible with a spin assignment of 5^+, making the 2284 keV state the likely correspondence with the 2290 keV one. The 174 keV energy difference between observed and predicted 5^+ states is within the typical range observed for USD calculations.

With increasing level density, it becomes more difficult to determine any clear correspondences between experimental and predicted states. The number of predicted and observed states is approximately equal below 4 MeV. There are no obvious signs of deviation with the USD predictions, except for a question about the 1^+ states discussed below.

B. "Missing" 1⁺ State

One curious difference with the shell model was observed in the β-decay study of Ref. [12]. Allowed β-decay branches were observed from the 0^+ g.s. of ^{26}Ne to three 1^+ states in ^{26}Na at 82.5, 1511, and 2723 keV. However, the shell model using the USD interaction predicts four 1^+ states below 3 MeV, as can be seen in Fig. 4. All four are predicted to have relatively strong β branches, so the nonobservation of one in a sensitive experiment is a clear disagreement. The three states with observed β branches agree very well in energy with the shell model states at 0, 1531, and 2720 keV. There are a number of candidates for the "missing" 2271 keV state in the present work. Two are within 100 keV and another four are within 300 keV. None of their decay modes would exclude an assignment of 1^+. However, such an identification still does not explain the lack of an observed β-decay branch. An alternative interpretation presented in Ref. [12] is an identification of the 2271 keV level with the experimental 2723 keV state, based on a closer similarity in β-decay log(ft) values. This implies a rather large energy mismatch of 450 keV. Either way, one or more of the shell model 1^+ states is mismatched considerably in energy or in β-decay strength.

The missing 1^+ state is more than an isolated curiosity. Three allowed β branches were observed from the 0^+ g.s. of ^{28}Ne to 1^+ states at 0, 2218, and 2714 keV in ^{28}Na [6]. Again, the USD shell model predicts four 1^+ states in this energy range at 92, 1658, 2258, and 2795 keV. As in ^{26}Na, three of these states agree rather well in energy with three of the observed states, and one is missing.

It is not possible to determine if this problem extends to ^{24}Na, because the Q value of the β decay from ^{24}Ne is only 2.47 MeV. Allowed β-decay branches were observed to two 1^+ states at 472 and 1347 keV [18]. The shell model predicts 1^+ states at 447, 1091, and 3210 keV. The first two probably correspond to the experimentally observed states with a moderately large energy difference of 256 keV for the second state. The third shell model state lies above the β-decay threshold, but experimental 1^+ states have been identified at 3413 and 3589 keV in other reactions.

V. SUMMARY

The level and decay scheme of $T_z = 2$ ^{26}Na was investigated using the ^{14}C(^{14}C, d) reaction at 22 MeV. Deuteron-γ and deuteron-γ-γ coincidences were observed using a Si charged-particle detector telescope and the Florida State University Ge detector array. γ-decay modes and precise energies were determined for most of the levels below 4 MeV previously observed in charge-exchange reactions, and several new states were observed. Angular distributions and decay patterns have helped to assign and constrain the spins of levels. Overall, there is reasonably good agreement with the s-d shell model using the USD interaction. A curious missing 1^+ state, or β-decay branch to it, mirrors a similar situation in ^{28}Na.

ACKNOWLEDGMENT

This work was supported in part by the National Science Foundation through Grants PHY-99-70991 and PHY-01-39950.

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